Double Bonanza in the LIGO Gravitational Wave Detectors

C. S. Unnikrishnan
Tata Institute of Fundamental Research,
Homi Bhabha Road, Mumbai 400005

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Abstract

Soon after the two advanced LIGO detectors were ready in September 2015 for a calibrated observation run, a giant gravitational wave burst hit the detectors and were duly recorded as nearly identical chirped signal wave spiralling up in frequency and amplitude from 35 Hz to 250 Hz, with a relative delay of 6.9 ms, well inside the light travel distance of 10 ms between the two detectors. The peak strain amplitude touched 10^{-21}, 50 times the base sensitivity at present. Analysis of the 200 ms event led to the unanimous conclusion that LIGO detectors saw gravitational waves from two orbiting and merging black holes of nearly 30 solar mass each, at a distance of about 1.5 billion light years. We sketch this double discovery of great scientific and astronomical importance - the terrestrial detection of gravitational waves with high SNR, ushering in the era of gravitational wave astronomy, and the discovery of a stellar mass binary black hole system, observed during their orbital evolution towards merger and then to the formation of a single stable black hole, all invisible to any other form of astronomy.

1 The discoveries

The direct laboratory detection of gravitational waves (GW) was a much awaited event by the entire physics community and the expectation ranged

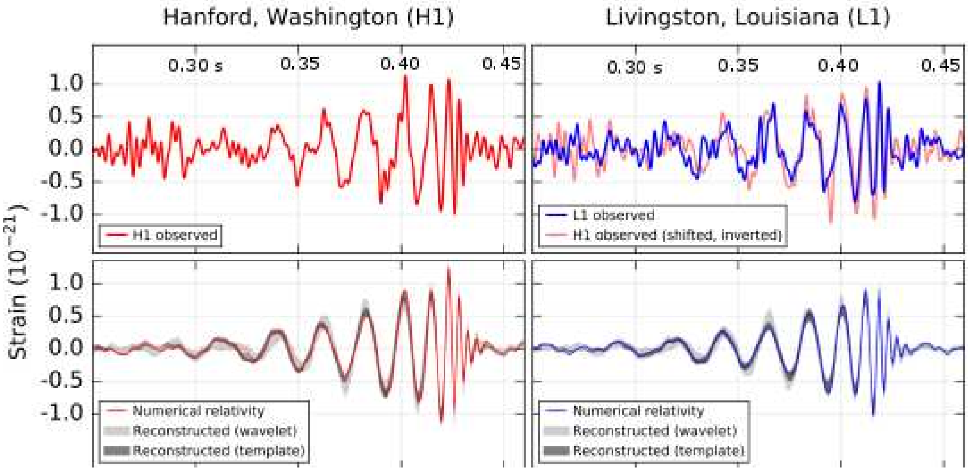

Figure 1: The strain data from the two detectors. Hanford detector is rotated approximately 90 degrees to Livingston detector causing 180 phase shift for the quadrupolar waves. Indeed, the observed signals correspond to this and one need inversion for the best match with the other, adding confidence that quadrupolar fields are detected.

from ‘very soon’ to ‘sometime before 2018’, after the advanced LIGO (aLIGO) detectors came into operation at their improved sensitivity and bandwidth last year. The aLIGO optical interferometer detectors are expected to reach their projected full sensitivity only in 2017, but the confirmed stability and improved range of observations during the commissioning last year lead to an engineering run in August-September followed by a science run during September 2015 - January 2016. The improvement in sensitivity ranges from a factor of 10 to 3, for gravitational waves with frequency between 30 Hz to 1000 Hz, which corresponds to the end stage orbital frequencies of binary neutron stars and black holes. After the calibrations and tests were completed, on September 14th, loud and clear strain signals were detected in both the interferometer detectors with a relative delay of 6.9 ms, well within the light travel time of 10 ms between the detectors.

The event is designated GW150914. Tiny by even interferometric standards, the signals exceeded signal to noise ratio (SNR) of 23 for the aLIGO detectors, reaching a peak strain of 10^{-21}, which is more than 100 times their base sensitivity. Though sophisticated waveform matching data analysis tools are developed and used in aLIGO detectors, this signal was notified within 3 minutes of their arrival by a simpler burst detection algorithm. The statistical probability for such an event occurring due to chance coincidences from noise, estimated from the rest of the data with noise, is less than 2×10^{-7}. A closer look soon confirmed two amazing discoveries [1], barely a week after the detectors were in their certified stable operation; one is of course that the detected signals are indeed of gravitational waves from a binary stellar system, and the other, unexpected by most, was that the source was a binary black hole system of nearly equal mass black holes of about 29 and 36 solar masses, at an estimated distance of about 410 Mpc (redshift 0.09). Thus, this loud event just happened to be exclusively for the eyes of aLIGO, unobservable in any electromagnetic spectrum. That this happened exactly hundred years after the critical months in which Einstein was completing his theory of gravitation - the general theory of relativity - was no strange coincidence; the advanced LIGO detectors were commissioned on schedule in the centenary year with enough sensitivity for such events for the first time.

2 The detectors

Gravitational waves have a quadrupolar nature and head on waves force free masses into motion such that masses azimuthally separated by 90 degrees on a circle move out of phase [2]. This makes the Michelson interferometer that measures the path difference ΔL between two perpendicular arms a natural detector of gravitational waves. The advanced LIGO detectors [3] are Michelson interferometers of arm length L of 4 km each, with light path folding of factor 300 implemented by Fabry-Perot cavities inside the Michelson arms. Thus the effective length exceeds 1000 km (about a fourth of the wavelength of gravitational waves) and the minimum detectable strain is determined by photon shot noise in the frequency range 50-1000 Hz and by thermally generated noise on the suspended optical elements at lower frequencies. The advanced LIGO detectors are the result of a major upgrade from the LIGO detectors that were operated until 2010. A comparable upgrade, with emphasis on achieving similar sensitivity in an overlapping bandwidth is underway at the Virgo detector as well. The major improvement is in the low frequency sensitivity, by a factor 1000 at 30 Hz to about factor 3 at 100 Hz, achieved by the enormous suppression of low frequency seismic and environmental noise in the range of 10 Hz to 100 Hz, employing active vibration isolation and improved passive isolation as well as reduction of thermal noise with high-Q suspensions and larger mirrors. Also, heavier mirrors reduced the radiation pressure noise. [4]. The Fabry-Perot enhancement is about a factor 2 more compared to initial LIGO. The present sensitivity at 40 Hz and 1000 Hz is about $2 \times 10^{-23} / (Hz)^{1/2}$ and the best sensitivity at about 200 Hz is $8 \times 10^{-24} / (Hz)^{1/2}$, achieved with input laser power of a modest 20 W, which is enhanced at the Michelson input to 700 W by a cavity power recycling technique [2, 3]. This corresponds to relative mirror motion of $3 \times 10^{-20} m / (Hz)^{1/2}$. The full projected sensitivity is another factor of 3 better, to be achieved in scheduled improvements (higher laser power, for example) during this year. The process of commissioning towards full sensitivity is laborious and technically complicated process because already the optical power held by the two mirrors of the Fabry-Perot cavity is 100 kilowatt and much larger power can distort the best of mirrors technically possible to fabricate, leading to unstable operation. Isolation from seismic and environmental noise is achieved by a combination of passive isolation consisting of low frequency springs and pendulums and active feedback isolation consisting of large number of sensors and actuators. The detectors at Hanford, Washington and Livingston, Louisiana are separated by about 3000 km (10.1 ms light travel time) and their orientation are such that one is rotated almost 90 degrees relative to the other, making the quadrupolar waves generating nearly out of phase (180 degree) response [1]. These exquisite and elaborate GW detectors are the result of 30 years of research and development, starting with the original experiments and proposals in the 70s. The large scale interferometers with sufficient sensitivity over a very large bandwidth like the LIGO detectors evolved from a technically and conceptually complete note by R. Weiss at MIT in 1972 [5]. The interferometer detector conceived and built by Moss, Forward and Miller in 1971 as a laboratory prototype [6] was already a match to Joseph Weber's pioneering and provocative resonant bar detectors and could reach displacement sensitivity of $10^{-14} m / (Hz)^{1/2}$ at 5 kHz with 100 μW of laser power. Formal proposals for the LIGO detectors [7] in the US and the Virgo detector [8] in Europe were initiated in 1989. aLIGO is funded by the National Science Foundation and Virgo by CNRS, France and INFN, Italy.

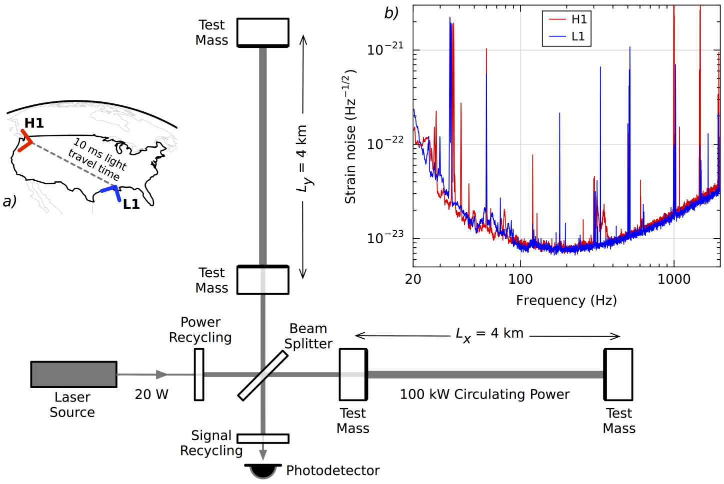

Figure 2: The optical schematic of the aLIGO detectors H1 and L1. Right insert shows the strain sensitivity. From reference 1.

3 Signal, Waveform and Noise

The source of the transverse gravitational waves, in relativistic gravitational theories and in particular in general relativity, is time dependent matter-energy quadrupole moment and the GW luminosity (total energy radiated in unit time) of a binary system in a quasi-circular orbit is given by $L = \dot{E} = 32GM^2r^4\omega^6/5c^5$ and the measurable strain at distance R is $h = \Delta L/L \simeq \frac{GMv^2}{Rc^4}$. This implies that as the system radiates waves, the orbit shrinks and the orbital frequency and the strain amplitude increase. Thus the expected response in a wideband interferometer detector is a chirp waveform for the motion of the mirrors, at double the orbital frequency. For example, one can expect a waveform ramping up in frequency and amplitude from $h \sim 10^{-23}$ at 50 Hz to $h \sim 10^{-22}$ at 500 Hz for a binary neutron star inspiral and merger. The magnitude of the strain is tiny, about 10^{-22} for a 10 solar mass object at 100 Mpc, at end stage orbital size of 10 Schwarzschild radius or so. Hence, the base sensitivity has to be better than 10^{-23} for detecting extragalactic binary neutron stars inspiral and merger, with SNR good enough for GW astronomy. This goal is constrained by various noise sources, all of which have been tamed fairly well in the aLIGO detectors, with some margin still ahead [9]. While thermal and radiation pressure noise dominate at low frequency, the detector is photon shot noise limited at frequencies above 100 Hz or so. Hence, the margin available in the laser power (<180 W) is expected to improve the high frequency sensitivity by a factor 2 to 3.

Though by chance, the first detection in the aLIGO detectors happened to be much louder than the base sensitivity of the well calibrated and stable detectors and this high SNR makes this particular event a detector and instrumentation triumph, needing very little of sophisticated and specialized data analysis for the deduction of the essential aspects about the nature and source of the gravitational waves. It was as if one hears a mild explosion while trying to listen for an imperceptible murmur. In fact, with only the fundamental formulae for the flux and strain, known from standard GR from early days, and the evolution of the bandpass-filterd waveform one can deduce surprisingly large amount of information already. Matching with the template waveforms calculated using relativistic post-Newtonian formalism and numerical relativity, along with sophisticated data analysis tools, are of course needed, an used, for the precise estimation of the parameters of the binary source.

4 Checks and confirmation

LIGO detectors are designed to detect rare events with signal strength typically too small to be seen without sophisticated data analysis methods and pipelines. Hundreds of sensors monitor the environment to map out noise from electromagnetic, seismic and other environmental disturbances. There was also the rare practise of injecting a synthesized signal, by a small authorized group of LIGO scientists, that mimics a genuine GW chirp signal into the interferometer, sometimes right at the interferometer mirrors by shaking them with actuators, without such information revealed to the other members involved in the analysis of detector state and data. The goal is to test the efficacy and readiness of all the detection and analysis pipelines and software. This is called a blind injection and the parameters of the injection is stored in a sealed envelope. Oblivious to this, the rest of the team analyses all events detected as candidates that cross the threshold criteria like signal to noise ratio, relative time delay between the detectors etc. It is only after confirmation or otherwise as an event, the information whether there was indeed a blind injection would be revealed. After the event GW 150914 went through the preliminary analysis as a candidate, it was confirmed that there was neither a blind injection nor inadvertent or intentional access to the detector system that could generate the observed signal.

5 The binary black hole

The confirmation that the source was a binary black hole (BBH) system with relatively heavy (36 and 29 solar masses) black holes, merged and gone from view for ever now, was indeed a surprise. The detailed arguments as to establishing this may be found in references [1, 10]. This discovery indicates a good detectable population of such systems and is sure to excite astrophysicists to reconsider models of black hole formation, especially in binary systems. The observed signal can be reproduced well when such a system is at a distance of about 400 Mpc (signal amplitude is just inversely proportional to the distance, as for electromagnetic waves). It is perhaps important to stress that this is the first observation and confirmation of existence of a stellar mass binary black hole system, adding much value to the already spectacular detection of the waves in a terrestrial GW antenna.

The largely sinusoidal chirp of the waveform indicates that the orbit eccentricity, if any, is small. In highly elliptical orbits, dominant emission is at closest approach with high velocity and results in more spiky nature of the waveform with higher harmonics. Lack of slower periodic modulations of the waveform (except the chirp) puts strong constraints on the magnitude and orientation of the spins, relative to the orbital angular momentum. If the individual black holes have large spins that are not perpendicular to the orbital plane, relativistic precessions will result in modulating the orientation of the orbital plane and will be reflected as modulations of waveform. However, an accurate estimate of spin related parameters requires fairly involved modeling and computations.

6 General Relativity and the aLIGO event

The general relativistic prediction for the nature and flux of gravitational waves is verified with great accuracy [11] by observing the orbital decay of the Hulse-Taylor binary pulsar system 1513+16. The BH-BH gravitational waves observed by aLIGO confirms the GR prediction with about 10% accuracy in a scenario involving black holes that approach each other to below 2 Schwarzschild radii, with orbital speed more than 50% of the velocity of light in a region with high gravitational potentials and curvature. All the parameters estimated from the waveform are consistent with general relativity. The large orbital angular momentum of the binary system, approximately $J = mr^2(t)\Omega(t)/2$ is very well determined from the relativistic Keplerian parameters and from the several cycles of the slow chirp waveform. During the evolution, significant fraction of angular momentum, along with the orbital energy, is radiated in gravitational waves. This is essentially $2E/\Omega$, or $2\hbar(E/\hbar\Omega)$ in terms of 'gravitons' of spin $2\hbar$. The remaining angular momentum and whatever spins the individual black holes go to make the spin of the final Kerr black hole. The dimensionless spin parameter $a = r_j/r_0$, with $r_j = J/Mc$ and $r_0 = GM/c^2$ is less than 0.7 in the GR estimate [1]. Numerical relativity calculations accurately model and calculate this and there is very good agreement with what one expects from the general theory of relativity, even though the computationally well determined final spin is not accurately measured directly from the 'ring-down' part of the waveform after merger.

The formation of blackhole from merger or collapse of matter is not spherically symmetric in general and one expects shaking away of these oscillating quadrupolar modes on way to the formation of a nice round BH, all visible in principle in the emitted gravitational waves after merger. The quasi-periodic oscillations of the forming black hole was investigated in the past by different researchers, with pioneering work from C. V. Vishveswara [12], W. H. Press [13] and S. Chandrasekhar [14]. The large signal from this event enabled LSC researchers to sieve out some indication of the ringdown towards the final black hole even though the SNR in this regions is not high enough for precision tests. In any case, the entire waveform is consistent with GR at about 10% level and this is reflected in similar accuracies of parameters estimated from the waveform using general relativistic calculations.

The parameters of the binary system and the final black hole are well estimated from the detailed analysis of the GW waveform or the relative motion of the mirrors of the interferometers. Considering that the astrophysical 'event' happened 1300 million light years away, this is a great achievement for the first catch in the detectors. The masses are 36 and 29 solar masses (10% accurate), and energy worth 3 solar masses was radiated in waves. At peak emission the energy output was 3.6×10^{49} Watts, which is equivalent to 200 suns worth mass converted to energy in a single second! (This level of luminosity lasts only for a few ms, and hence the energy converted at peak is equivalent to less than two solar masses). That makes the GW150914 event a thousand times more powerful than the brightest gamma-ray bursts. The total energy radiated in gravitational waves (estimated from the observed waveform and estimated distance) is about 5% of the total mass energy of BBH system. It is perhaps important to point out that no matter is directly converted to energy and the entire radiation comes from the gravitational potential energy. After all, these are black holes and no matter can be released out.

One difference between the optical observation of the decay of binary pulsar and this direct detection is that the orbital decay is sensitive to the total energy radiated away, including hypothetical scalar waves or other possibilities in theories different from general relativity. The detectors on the other hand are designed to be most sensitive to the quadrupolar gravitational waves of transverse nature and for a source position where this sensitivity maximizes, the detectors are fairly insensitive to the scalar waves. Therefore, detailed modeling is required to directly address accurate tests of alternate theories and a rigorous analysis requires starting from exact premises of particular theories.

7 The LSC and IndiGO-LSC

The LIGO Scientific Collaboration (LSC) is a group of more than 1000 scientists from more than 90 universities and research institutes around the United States and in 14 other countries including India. The LSC detector network includes the two aLIGO interferometers and the GEO600 detector in Hannover, Germany. Several conceptual and technical developments for the LIGO detectors were contributed by the GEO team that includes scientists at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Leibniz Universität Hannover, along with partners at the University of Glasgow, Cardiff University, the University of Birmingham, other universities in the United Kingdom, and the University of the Balearic Islands in Spain. There is also significant contributions to LIGO from the Australian Consortium for Interferometric Gravitational Astronomy. In addition, the Virgo collaboration that operates the 3-km Virgo detector in Cascina, Pisa, Italy joins hands to form the larger LIGO-Virgo collaboration and publishes most results jointly.

The current participation of Indian scientists in LSC is under the IndIGO (Indian Initiative for Gravitational Wave Observations) umbrella. The gradually expanding course of gravitational wave research in India, with significant contributions to waveform calculations, data analysis and an impeccable record of collaborative research and training, is imprinted in the aLIGO discoveries and is well-acknowledged in the discovery paper. The IndIGO consortium that originated in 2009 to bind together and take forward GW research in India has now more than 120 members and about half of them are engaged in experimental activities in various fields relevant for GW detectors. About 60 of these are already active members of the LIGO Scientific Collaboration (LSC) and 37 are co-authors in the discovery paper. This includes senior researchers and engineers as well as post-doctoral fellows and graduate students. IndIGO's strong presence in the LSC is due to the commendable and continued history of involvement in theoretical work and data analysis as well as due to the intense work that has been put in to propose and realize the LIGO-India GW detector project, taken up in 2011. This was at a point of realization that there was a significantly large community of GW scientists involved in advanced calculations and data analysis techniques as well as several scientists and engineers keen to direct their expertise in optics and precision metrology towards GW research in India, who can come together and seek support for the construction and operation of an advanced detector in India. The viability of this dream was well-founded on the history of nearly three decades of gravitational physics research in India.

Bala Iyer, who was at RRI, Bangalore, was a key contributor to precision calculations [15] of exact shape of the gravitational waves emitted by orbiting astrophysical sources in the 90s. These calculations are so complicated, both conceptually and computationally, that only a few people, spread over two or three groups in the world had ventured into such studies. Recent developments in numerical relativity have of course enormously improved the present scenario. Searching whether there is a genuine signal in the usually noisy data by scanning the data with such characteristic waveforms, looking for the best match [16], was pioneered by Sanjeev Dhurandhar at IUCAA, Pune and his group. The large theoretical community of GW researchers in India today was seeded by these early research.

Over the last decade the Indian gravitational-wave community has spread to a number of educational and research institutions in India. These include CMI Chennai, ICTS-TIFR Bangalore, IISER-Kolkata,IISER-Trivandrum, IIT Gandhinagar, IPR Gandhinagar, IUCAA Pune, RRCAT Indore and TIFR Mumbai. IUCAA and ICTS-TIFR host LIGO Tier-3 grid computing centers. Major contributions of Indian scientists include the development of techniques to coherently combine and analyze the data from multiple observatories, development of hierarchical search methods that allow us to progressively dig into the data, techniques for making sky maps of stochastic gravitational waves, formulating methods to accurately test Einstein's theory of general relativity using gravitational-wave observations, modeling gravitational-wave signals by combining post-Newtonian calculations with large-scale supercomputer simulations, devising strategies to extract astrophysical information from a joint electromagnetic and gravitational-wave observation of a source.

The gravitational experiments group of TIFR, led by R. Cowsik, pioneered precision experiments to test gravity theories in India in the mid-eighties with special purpose laboratories and novel instruments [17]. TIFR funded a prototype interferometer GW detector, proposed by IndIGO-LSC members C. S. Unnikrishnan and G. Rajalakshmi in 2011. This new laboratory and prototype instrument are expected to play a significant role in training and research that support the LIGO-India project. The group has contributed actively to the LIGO-India project proposal.

A number of IndIGO scientists have contributed to the analyses in the double discovery paper to decipher the information about the binary black hole merger event encoded in the detected gravitational waves [18]. The analysis on several fronts confirm that even a most exotic event like the inspiral and merger of two black holes proceeded along the theoretical expectations in general relativity.

8 GW detector network

The only aspect that could have made this detection more spectacular, without doubt, is the identification of the location of the source in the sky. With just 2 detectors we have to be satisfied with a band of possible locations, determined by just one relative delay between the detectors, convolved with the sensitivity and beam pattern of the two detectors. Though such sky bands with location uncertainty of 600 square degrees were circulated to several collaborations that have prior MoU with LSC for electromagnetic follow up, no optical counterpart was detected, understandably. (There is report of a detected transient in X-rays above 50 keV by the Fermi Gamma-ray Burst Monitor, albeit with a delay of 0.4 s and then lasting for a second [19]). Whether a genuine connection or not, there is much in expectation for the

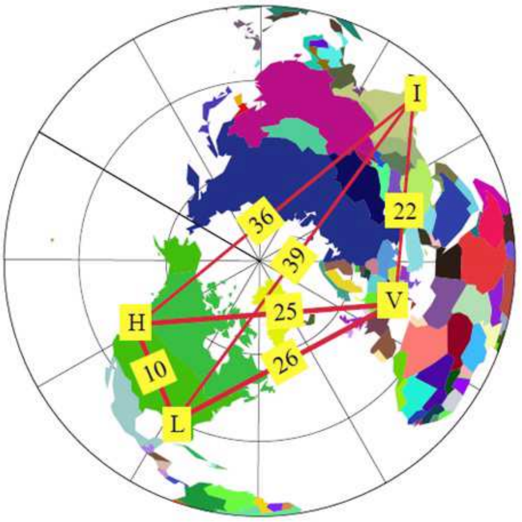

Figure 3: Global GW detector network baselines in light ravel time (ms), relative to detectors L!, H1, Virgo and the future LIGO-India.

X-ray instruments on board the Indian multi-wavelength astronomy satellite Astrosat. The next big discovery from LIGO is expected to be the identification of an electromagnetic signal (such as a gamma-ray burst) associated with a gravitational wave event. However, this requires a global network of detectors with intercontinental separations to localize gravitational wave events accurately on the sky. Clearly, we need more detectors that can match the exquisite and essential sensitivity of the two aLIGO detectors, with good overlap with their frequency range. The international science community is unanimous that the key to the future of gravitational wave astronomy will be a gravitational wave detector network spread over the globe with capabilities for localizing the source in the sky, which can then be identified with electromagnetic wave telescopes.

The advanced Virgo detector is expected to become operational in 2017, with good overlap of sensitivity with the aLIGO detectors. This will enable the first phase of gravitational wave astronomy with source location identification with a precision of 10 square degree or so in many parts of the sky. Improvement towards square degree precision requires more aLIGO like detectors and this highlights the importance of early deployment of detectors like LIGO-India. The cryogenic KAGRA underground GW detector [20] below Kamioka mountains, Japan is expected to become online by 2018. The present scenario envisages at least 5 aLIGO level detectors, with slightly different sensitivities and frequency ranges, operational by 2022 and the next decade of astronomy will be aided and indeed might be dominated by GW based astronomy.

9 The new wave in astronomy and LIGO-India

aLIGO detectors have been operating in their first phase of observational run (O1) during September 14, 2015 to January 14, 2016. The continuing analysis of the full data will give a good indication of expected rates of such events and it seems clear that the aLIGO detectors at their full sensitivity will regularly detect gravitational waves from sources up to a Gpc, perhaps more than an event per month. This is exciting for gravitational wave astronomy because a good fraction of these sources, involving binary black holes, may not be visible anywhere in the electromagnetic spectrum.

Even this first event in aLIGO detectors proves amply that gravitational wave astronomy has started and has asserted as an independent and essential window to the high energy stellar evolution events in the universe. LIGO has opened up a fundamentally new observational window to the Universe. This has the potential to revolutionize our understanding of astrophysics, cosmology and fundamental physics. If the event rate determinations based on the signals so far turns out to be stable in the long run, one can expect a reliable detection of several events every year in the aLIGO detectors operating at their full sensitivity [21]. Though the BH-BH type of events may not be visible to electromagnetic telescopes, events involving binary neutron stars are expected to show associated signals in telescopes spanning the entire electromagnetic spectrum. However, source localization is the key to successful follow-ups and integrated multi-wavelength multi-wave astronomy and this is indeed the future focus.

One of the key installations to realize a network with aLIGO capabilities is the ambitious LIGO-India project [22, 23]. Proposed in 2011, the LIGO-India project aims to build an Advanced LIGO detector on Indian soil in collaboration with LIGO-USA and its international partners Germany, UK and Australia targeted to start joint observation with the US detectors by

2022. LIGO-India will be the first International frontier science experiment on Indian soil, and will involve cutting-edge technology in lasers, optics, ultra-high vacuum and control system engineering. The project will bring together the best of fundamental science and high-end technology available in the country at national research laboratories, IITs, IISERs, universities and industry. LIGO-India will involve huge Indian industry involvement. The Department of Atomic Energy (DAE) and the Department of Science and Technology (DST) have joined hands to support this mega-science project. Almost the entire cost of the project will be expended in industries and laboratories within the country. It would serve as an internationally visible flagship for Industry-Academia partnership. Lead institutes for the proposal are IUCAA, IPR and RRCAT, in collaboration with the IndIGO consortium. IUCAA is responsible for site selection (IISER-Kolkata contributing in seismic characterization), data analysis and computing facilities, science and human resource development; IPR for civil infrastructure and facilities, vacuum system and mechanical engineering; RRCAT for the optics, detector integration, installation and commissioning. Teams at the three lead institutions have been intensely involved in taking forward all initial tasks related to the project. The proposal was cleared by the Union cabinet soon after the discovery, with an "in-principle approval" for the LIGO-India project, and this will give the much needed big boost to the LIGO-India detector project.

10 Acknowledgments

This article was compiled with published information from the LSC in the detection paper and some of the companion papers, the LSC and IndIGO press releases and also with input from several colleagues in the IndIGO consortium. Updates and details can be consulted at the IndIGO website www.gw-indigo.org and the LSC website www.ligo.org.

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